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1979 R K HANSON, C T BOWMAN F49620-78-C-0026

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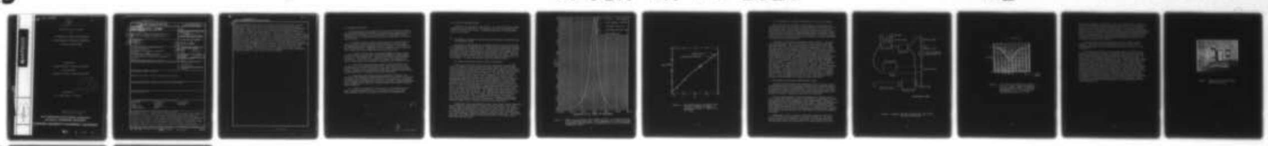

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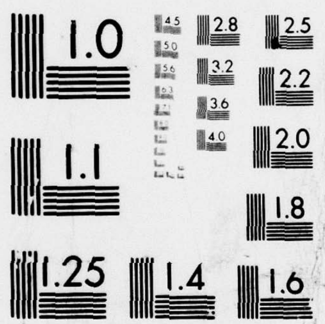

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Interim Scientific Report

on

DEVELOPMENT OF COMBUSTION DIAGNOSTICS AND APPLICATION TO TURBULENT COMBUSTION

Contract F49620-78-0026

Prepared for

Air Force Office of Scientific Research

For the Period

February 16, 1979 to September 30, 1979

Submitted by

R. K. Hanson and C. T. Bowman

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HIGH TEMPERATURE GASDYNAMICS LABORATORY
MECHANICAL ENGINEERING DEPARTMENT
STANFORD UNIVERSITY ■ STANFORD, CALIFORNIA

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COMBUSTION	TEMPERATURE	SPECTROSCOPY
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CARBON MONIXIDE	LASER	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Measurements with a tunable diode laser absorption system have been conducted in steady, fluctuating and sooting atmospheric-pressure flames produced in either a flat flame or a slot burner. Parameters measured include temperature, CO species concentration and CO spectroscopic parameters (line strengths and collision half widths). The measurements involve rapidly scanning the narrow-linewidth diode laser across individual vibration-rotation lines in the fundamental band of CO at 4.6 microns to record fully-resolved absorption line profiles in times as short as 100 microseconds. A conventional microprobe

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sampling system has been used to monitor CO and CO_2 concentrations to enable comparisons between laser-based and conventional probe-based measurements; thermocouples have been used to allow comparisons with laser-based temperature measurements. Results in fuel-rich flames show good agreement between the laser-based and probe-based measurements. Work is in progress to extend the measurements to fuel lean stoichiometries. Work has progressed on assembly and checkout of a new facility for studies of the dynamics of fluctuating or turbulent combustion flows. The facility generates a two-dimensional shear flow which will be used to study the coupling between fluid dynamic and chemical processes in a turbulent mixing layer. The selection of the two-dimensional geometry should enable use of line-of-sight optical techniques including diode laser spectroscopy. New work has been initiated to develop a tunable dye laser system for high-resolution absorption spectoscopy of combustion gases at visible and near-ultraviolet wavelength. The system has been assembled and initial experiments to measure sodium in a flat flame burner are underway.

1.0 RESEARCH OBJECTIVES

This program provides fundamental research in the area of advanced non-interfering optical diagnostics, particularly for application to the measurement of chemically reacting turbulent flow parameters and the interpretation of combustion dynamic phenomena. Objectives of the work are as follows:

a. Develop and apply tunable diode lasers for the measurement of major and minor species concentrations and temperature under steady, fluctuating and sooting combustion conditions. Species will include CO, CO_2, and possibly H_2O. Experiments will be conducted in flat-flame and slot burners and in a two-dimensional reacting shear flow.

b. Utilize the diode laser to measure fundamental spectroscopic parameters (line strengths and collision halfwidths) of combustion gas species in a flat-flame burner. Species will include CO and possibly CO_2 and H_2O. These data are required for proper interpretation of species concentration and temperature measurements in combustion flows.

c. Investigate coupling effects between reaction kinetics and turbulence in a two-dimensional shear flow. Experiements will be conducted using CO or NO in one reactant stream and O_3 or O_2 in the other stream. Diagnostics will include the diode laser, high-speed photography, conventional hot-wire anemometry and a laser anemometer.

d. Investigate and apply laser-based diagnostic techniques for spatially- and temporally-resolved measurements of temperature and species concentrations in turbulent reacting flows. Techniques to be considered are fluorescence and variations of Raman spectroscopy including spontaneous Raman, coherent Raman (CARS) and stimulated Raman, and tunable UV/visible laser absorption.

e. Compare measurements obtained with new laser techniques with those from existing methods (e.g., conventional spectroscopy, and point sampling probes for temperature and species concentrations).

2.0 STATUS OF RESEARCH EFFORT

Research is in progress on two topics: (1) laboratory flame studies using tunable laser absorption spectroscopy; and (2) an investigation of turbulent reacting shear flows. A summary of progress in these program areas follows below.

2.1 Development of Tunable Laser Absorption Spectroscopy and Applications to Laboratory Flames

During this reporting period, we have continued to make good progress in the development and application of tunable laser absorption spectroscopy as a diagnostic for combustion flows. Significant accomplishments include successful diode laser measurements of CO concentration and temperature in a variety of steady, fluctuating and sooting flames, and initial dye laser measurements of Na lineshapes and concentration in a flat flame. Details of completed work have been given in recent publications (see Section 3 of this report). A summary of relevant activities follows below:

a) Species Measurements with a Tunable Diode Laser

Carbon monoxide concentrations have been measured in the postflame region of laminar, premixed methane/air flames using both tunable diode laser absorption spectroscopy and conventional probe sampling. The optical technique employed a diode laser tuned to specific vibration-rotation lines in the fundamental band of CO at 4.6 microns. The data for each fully-resolved absorption line were analyzed by computer to obtain a best-fit Voigt profile (as shown in Fig. 1 for a representative case), thereby determining simultaneously both the CO partial pressure and the collision-broadened halfwidth for the line under flame conditions. The agreement between the laser-based value for CO and the chemical equilibrium value computed using the measured fuel and air flowrates was good, as shown in Fig. 2. In the sampling experiments, combustion gases were extracted using both an uncooled, aerodynamically-quenched quartz microprobe and a water-cooled stainless steel microprobe. The sampled gases were analyzed for CO and CO_2 using NDIR instruments. The sampling probe measurements, which were made in both lean and rich flames, yielded total carbon consistent with the input stoichiometry, but indicated substantial conversion of CO to CO_2 in the probe. The experiments with rich flames have been completed and are being written up for publication. Additional experiments with lean flames will be conducted within the next few months.

In addition to the experiments in steady, clean flames already described, laser absorption measurements of CO have also been carried out in a fluctuating flame environment and in a heavily soot-laden flame. The objective in these initial experiments has been to show the versatility of tunable laser absorption as a combustion diagnostic technique under conditions where most other techniques (conventional and laser-based) would fail. Preliminary experiments have been highly successful and results recently have been published (see Section 3).

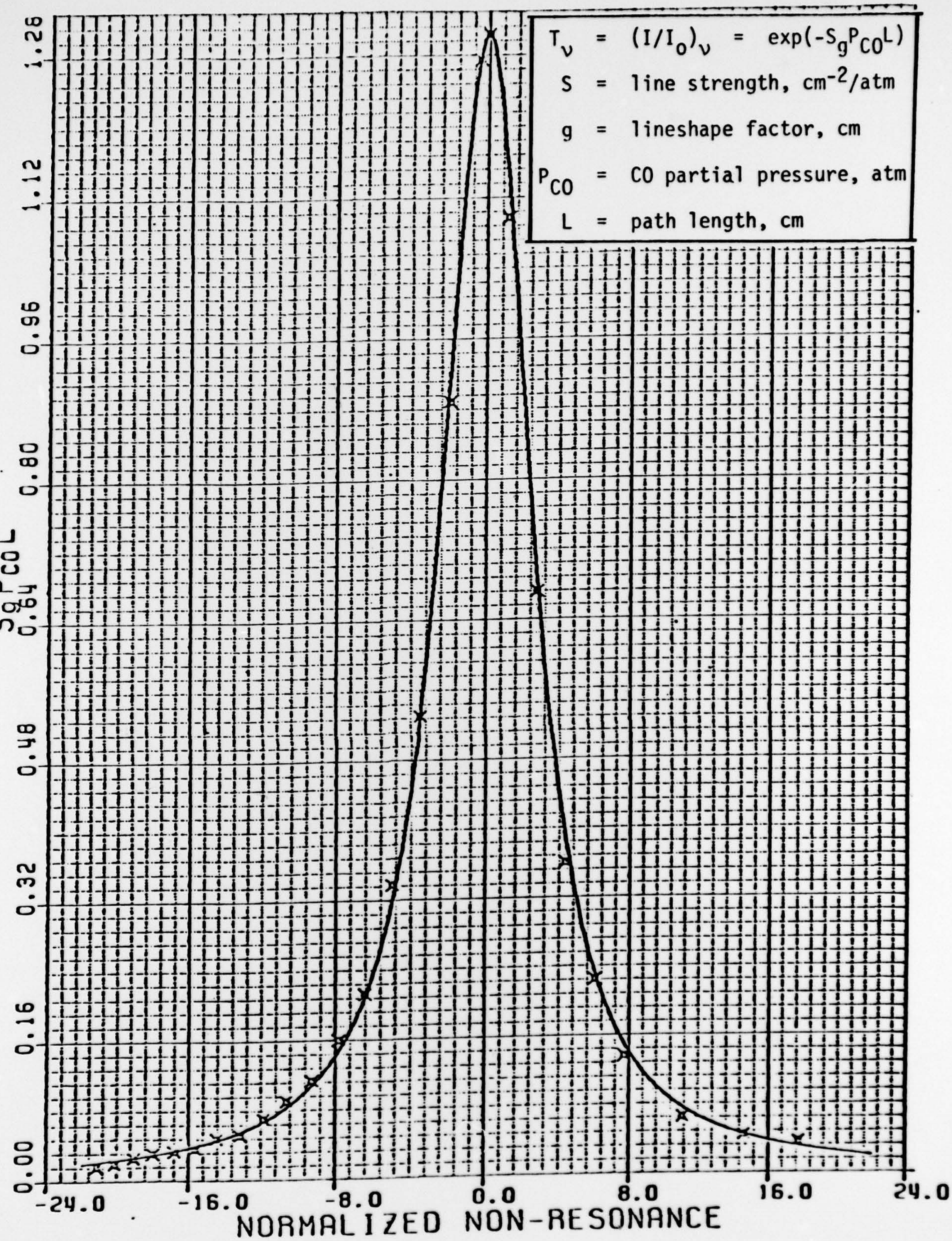

Figure 1. Voigt fit to absorption line profile for CO (v = 1←0, P(7) at 2115.63 cm^{-1}) in CH_4/air flat flame. Flame conditions are: T=1850 K, P= 1 atm and ϕ=1.24. Inferred results are P_{CO}=0.0421 atm, a=2.66 and $2\gamma(1850)$ = 0.0393 cm^{-1}-atm^{-1}.

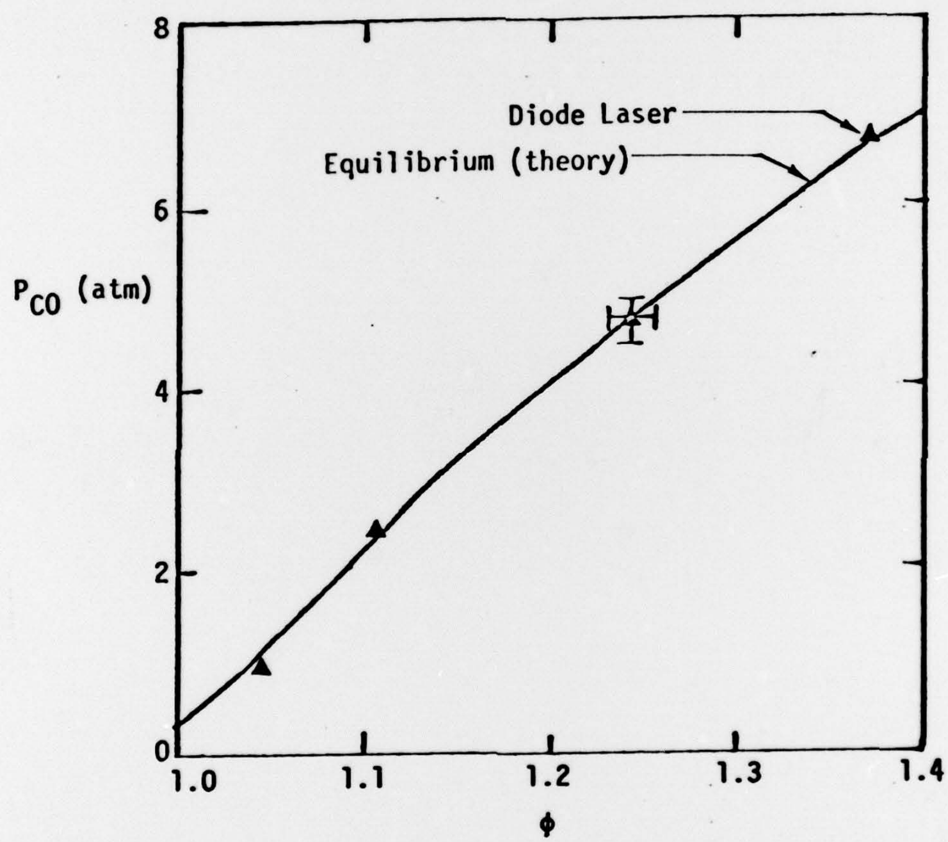

Figure 2. CO partial pressure in CH_4/air flat flame as a function of fuel-air equivalence ratio; T = 1875 ± 25 K, P = 1 atm.

b) Development of a Tunable UV/Visible Laser Absorption System

The success of our work with tunable diode laser absorption has stimulated interest in developing a laser absorption system for the ultraviolet and visible regions of the spectrum. Such a device would be particularly useful for measuring low concentrations of radical species and thus would complement the infrared diode laser system which is best suited for species present in higher concentrations. During this reporting period we have assembled such a system and have initiated experiments to checkout the system components.

A schematic of the overall system is shown in Figure 3. An argon-ion laser (4W, multi-line) is used to pump a ring dye laser (Spectra Physics Model 380A). The narrow-linewidth (single axial cavity mode) dye laser output is repetitively modulated in wavelength over a single absorption line using a standard scanning electronics package available with the dye laser. For UV absorption studies, an intracavity frequency doubling element will be used. The laser wavelength is set using a monochromator and scanning interferometer in conjunction with the observed absorption record. Variations in laser power during each modulation cycle are minimized with a commercial dye laser light regulator which is connected to the pump laser power supply through a feedback control circuit. A ratioing technique (see Fig. 3) is used to minimize the effect of any residual power variations. A direct measurement of the change in wavelength during each scan, needed to infer the absorption line halfwidth, is made with a conventional spectrum analyzer or Fabry-Perot etalon. The outputs of the spectrum analyzer and the detectors are recorded on a digital oscilloscopy or signal averager. A recently obtained result for absorption by Na in a flat flame burner is shown in Fig. 4. To our knowledge, these are the first fully-resolved atomic absorption lines recorded in a flame by a laser technique.

2.2 Investigation of Turbulent Reacting Shear Flows

Coupling of fluid dynamic and chemical processes is a major factor in governing performance and pollutant emissions from combustion devices. At the present time, our understanding of the nature of this coupling is insufficient to permit extrapolation of results obtained from one combustion device to other devices or to allow quantitative prediction of the effects of changes in operating conditions on performance.

In the present program, we are investigating the coupling between fluid dynamic and chemical processes in turbulent reacting flows. Several flow configurations were considered for the investigation, including axisymmetric jets and two-dimensional shear layers. Extensive experimental investigations of the structure of non-reacting, two-dimensional shear layers have been reported in the literature. A principal observation in these studies was the existence of large-scale, two-dimensional, organized structures in the mixing layer which significantly influence entrainment and mixing.

Measurements on the structure of turbulent flames have shown the presence of both large-scale and small-scale fluctuations. The qualitative similarities of turbulence structures in two-dimensional, non-reacting shear layers and those found in the shear layers of turbulent

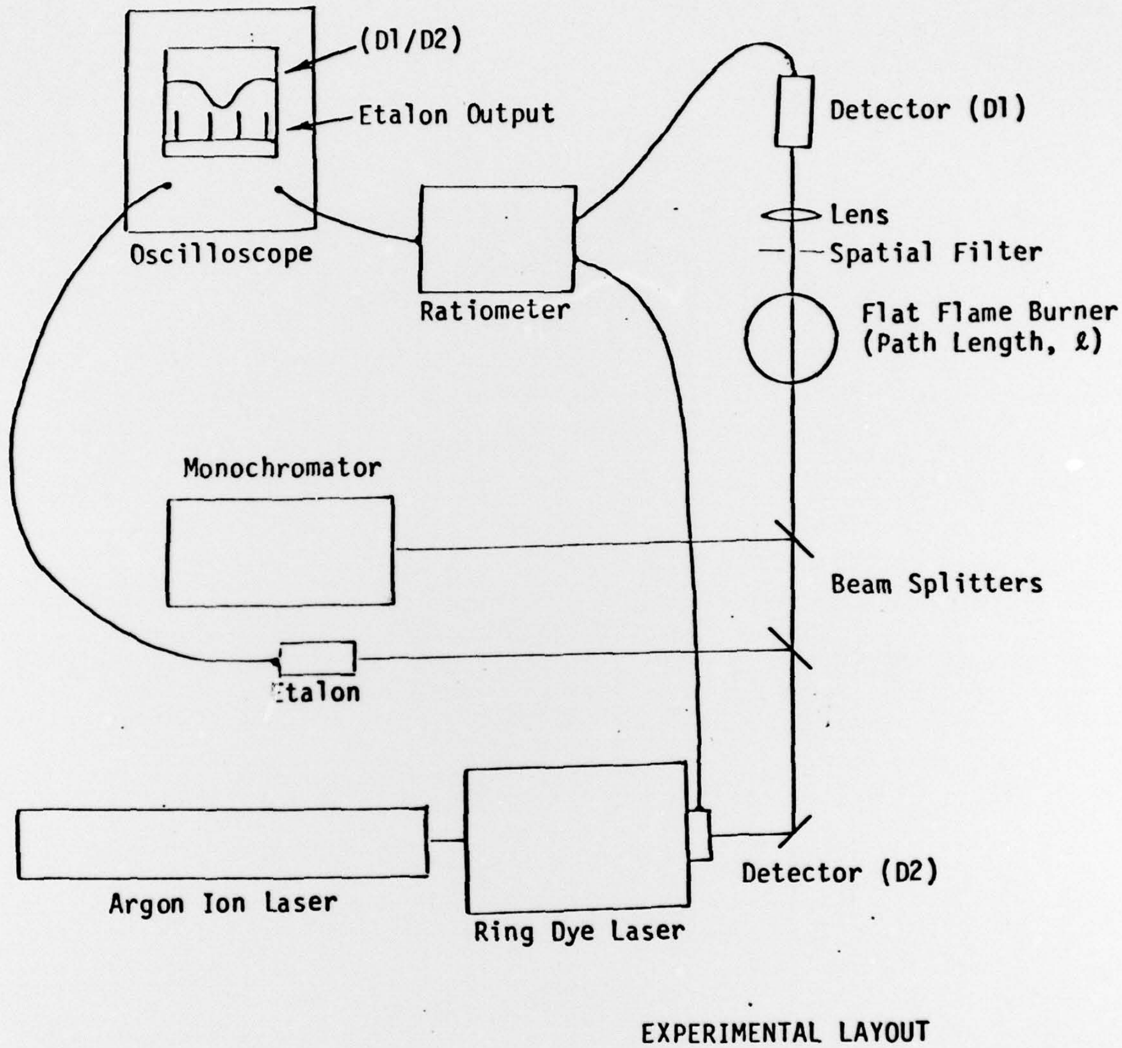

Figure 3. Schematic diagram of tunable dye laser system for flame measurements.

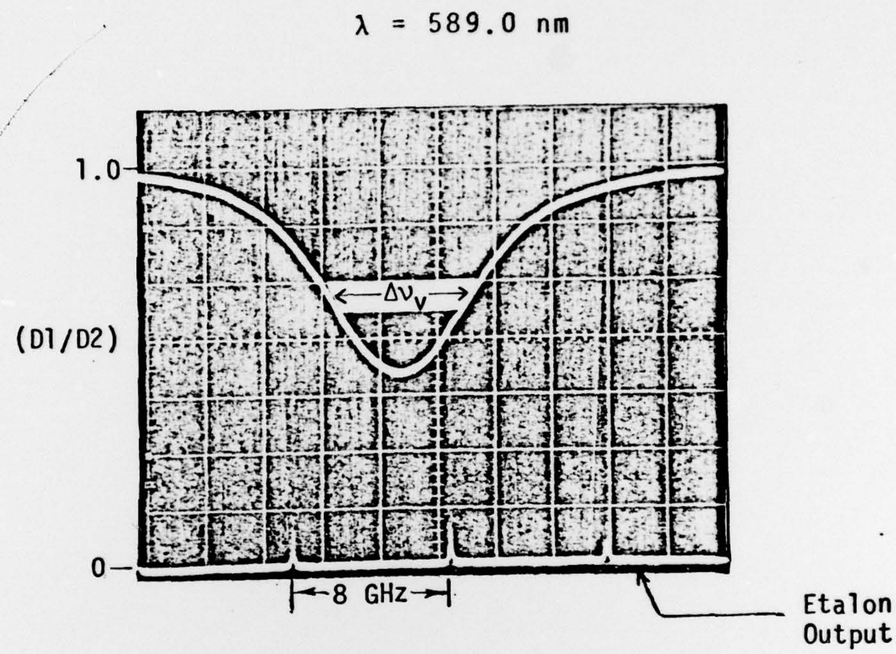

Figure 4. Fully-resolved absorption line record of Na in a flame. The Na concentration was approximately 10^{12}/cc, the optical pathlength was 8 cm, and the infrared line halfwidth was $\Delta\nu_V = 7.5$ GHz.

flame burners suggest that measurements on two-dimensional reacting shear layers should provide considerable insight into the effects of turbulence structure on reaction rates in turbulent flames. From an experimental standpoint, the two-dimensional geometry offers several distinct advantages. There is extensive documentation of the turbulence structure of geometrically similar non-reacting flows. In addition, the geometry is amenable to advanced optical diagnostic techniques currently available in our laboratory for simultaneous, non-perturbing, in situ measurements of species concentration, temperature and velocity.

A two-dimensional shear flow facility has been designed and constructed. The experimental configuration, Figure 5, consists of two atmospheric-pressure gas streams separated by a splitter plate in a rectangular duct.

Tests have been conducted on nonreacting flows to characterize the approach flow and the flow field structure downstream from the splitter plate using conventional hot-wire anemometry. Subsequent tests will be conducted with trace amounts of NO or CO in one of the gas streams. In these tests, time-resolved measurements of the trace species concentration will be obtained using the tunable diode laser. These measurements will be used to develop the mean concentration distributions which will be compared with existing probe data for two-dimensional turbulent mixing layers to validate the diagnostic techniques. In addition, time-resolved concentration measurements in the mixing layer coupled with the velocity measurements and flow visualization data will provide information on the entrainment and mixing process. Of particular interest is the degree to which the surfaces of large-scale eddies in the mixing layer serve to separate the two fluid streams, i.e., the relative rates of entrainment of fluid by the large eddies and rates of small-scale mixing. These observations will assist in the development of a phenomenological model for the mixing layer.

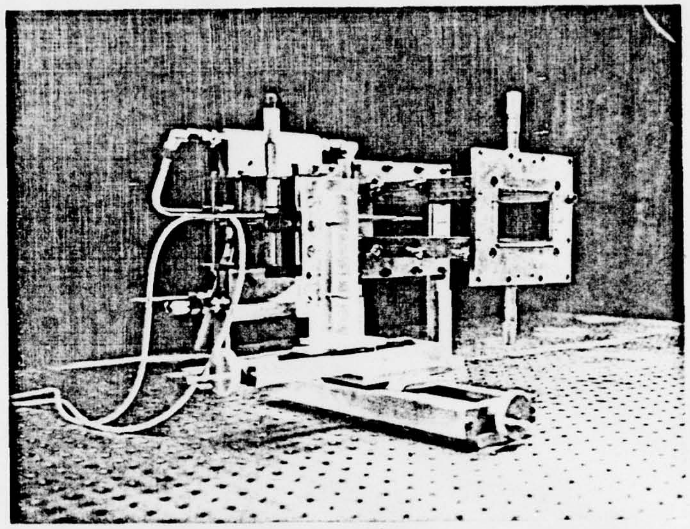

Figure 5. Photograph of two dimensional shear flow facility.

3.0 PUBLICATIONS

1. R. K. Hanson and P.K. Falcone, "Temperature Measurement Technique for High-Temperature Gases Using a Tunable Diode Laser," Applied Optics 17, 2477 (1978).

2. S. M. Schoenung, R. K. Hanson and P. K. Falcone, "CO Measurements in Combustion Gases by Laser Absorption Spectroscopy and Probe Sampling," Western States Section/Combustion Institute Paper 78-46, October 1978, Laguna Beach, CA. To be submitted to Combustion Science and Technology.

3. R. K. Hanson, "Combustion Gas Measurements Using Tunable Laser Absorption Spectroscopy," AIAA Reprint 79-0086; presented at 17th Aerospace Sciences Meeting, New Orleans, January 1979.

4. R. K. Hanson, P. L. Varghese, S. M. Schoenung and P. K. Falcone, "Absorption Spectroscopy of Combustion Gases Using a Tunable Infrared Diode Laser," American Chemical Society Symposium Series, "Laser Probes in Chemistry," in press (1979).

5. R. K. Hanson, "Absorption Spectroscopy in Sooting Flames Using a Tunable Diode Laser," submitted to Applied Optics (1979).

4.0 PROFESSIONAL PERSONNEL

The faculty involved in this research are Professors R. K. Hanson and C. T. Bowman; participating graduate students are Ms. Susan Schoenung and Mr. Steve Masutani.

5.0 PROFESSIONAL INTERACTIONS

a) Talks Given;

R. K. Hanson, "Absorption Spectroscopy of Combustion Gases Using a Tunable Infrared Diode Laser," invited talk presented at meeting of the American Chemical Society, Wash. D. C., Sept. 1979.

R. K. Hanson, "High-Resolution Absorption Spectroscopy in Combustion Gases," invited talk at FACCS meeting, Philadelphia, Sept. 1979.

b) Visitors:

Visitors during this 6-month period have included Drs. Dan Hartley and Mike Gusinow from Sandia Livermore Laboratories, Dr. Dave Mann from the Air Force Rocket Propulsion Lab, Dr. John Shirley from United Technology Corporation and Dr. Paul Schrieber from the Air Force Aeropropulsion Laboratory.

6.0 APPLICATION OF NEW KNOWLEDGE

This AFOSR-supported research has yielded new techniques for species and temperature measurement in high-temperature flows of general utility in aerospace technology.